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ALPINE SNOW AND HYDROLOGIC RESEARCH

at the

FORT COLLINS RESEARCH CENTER

Rocky Mountain Forest and Range Experiment Station

(A Project Analysis and Working Plan)

by

M. Martinelli, Jr.

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PREPARED:

May 1, 1957

APPROVED: DATE:

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INTRODUCTION

The term "alpine", or "high alpine", when used herein will include all areas above the upper limits of the true forests. Thus, it includes both the subalpine transition zone with its scattered patches of decumbent and scrubby coniferous trees, and the true alpine area above the upper limits of all tree growth. This broad definition of the term is justified for these studies because of the great similarity of the climatic, geologic, edaphic, and hydrologic characteristics of the two vegetative zones. (Fig. 1).

The term "high alpine" is often used in avalanche reports and studies when referring to the alpine area in the Rocky Mountains. This more complete term emphasizes the extreme elevation of the Rocky Mountain alpine in comparison to similar areas in the Wasatch and the coastal mountains.

The lower limit of the alpine zone in the Rocky Mountains is about 11,800 feet in southern Colorado. It drops to about 11,000 feet in northern Colorado, and to about 9,500 feet in northern Wyoming. These altitudes will often vary considerably with local topography. The lowest 500 feet of this zone usually supports the wind-trimmed trees of the subalpine transition zone.

Schwan and Costello (1951) state that there are approximately 5 million acres of alpine area in the Rocky Mountains. At least 2.25 million acres of this alpine area are in Colorado; about 2.2

Figure 1.--The alpine includes all the area above the elevation of the true forest. It is composed of windswept, grassy ridges, snow-filled depressions, and a fringe of wind-trimmed trees along the lower edge.

million acres occur in Wyoming; and there are small isolated areas in New Mexico. (Fig. 2).

THE IMPORTANCE OF THE ALPINE AREA

Abundant precipitation, steep slopes, vegetative types, and permeable soils make the alpine zone an important source of water in a semi-arid region. Schwan and Costello (1951) estimate that each acre of alpine area contributes 1-1/2 acre-feet of water annually. Stated in another way, it is estimated that 20 percent of the stream-flow in Colorado originates from the 3-1/2 percent of the surface area above timber line. Lawrence (1953), in his study of power sites on the Crystal River in Colorado, stated that the mean annual runoff above Marble (7,908 feet) was 44 inches for the period 1911-1915. From these runoff figures and an average annual precipitation of 27 inches at Marble, the annual precipitation for the drainage area above 7,900 feet to be 59 inches and that for the mountain peaks to be in excess of 75 inches.

Dodds (1917) reports the average annual precipitation at Corona, Colorado (11,680 feet) to be 44 inches. For the 6 years of record an average of 16.6 inches fell during the spring months of March, April, and May.

The alpine zone also provides considerable grazing for domestic sheep and, to a lesser extent, cattle. Ever since early pioneer days, alpine meadows have been an important source of summer range. It is estimated that about 600,000 sheep graze these meadows annually. Economically, grazing would probably rank second to water production in the evaluation of the alpine zone. (Fig. 3)

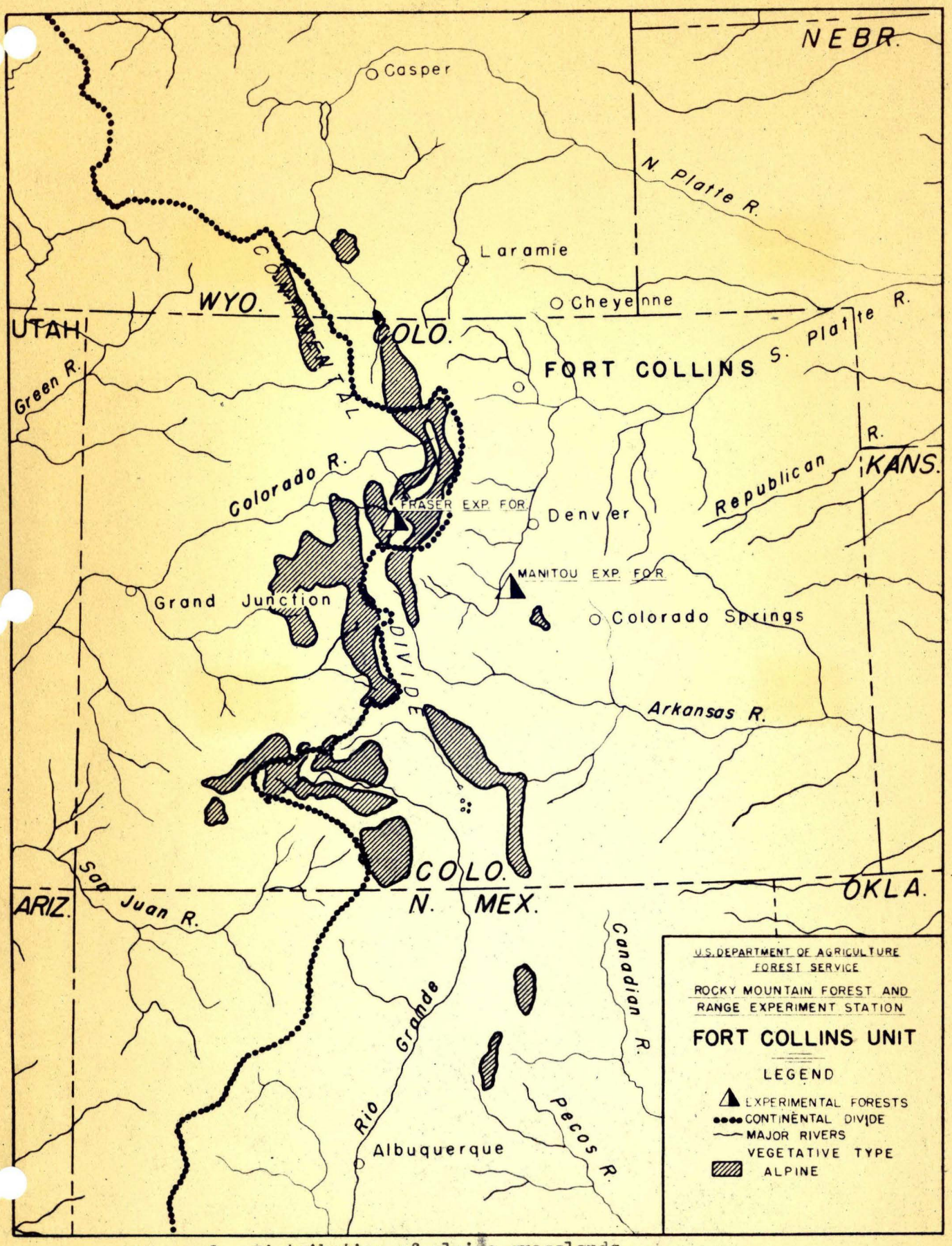

Figure 2.--Distribution of alpine grasslands.

Map #6

Figure 3.--Grazing is one of the important benefits derived from the alpine. For years these areas have been an important summer range for domestic stock.

The alpine zone is becoming more and more important as a source of esthetic and recreational activities. As the population of the Rocky Mountain region continues to increase, the "high country" above timber line is used more and more by large numbers of hunters, fishermen, mountain climbers, tourists, and skiers. There are indications that, in the near future, these recreational aspects of the alpine will increase greatly in importance. In recent years well over 1/4 million skiers annually have used the winter sports facilities in Colorado alone. Although many of these winter sports areas are not completely in the alpine, alpine avalanche conditions play a vital part in their safe operation and in the travel to and from them. The number of fishermen, hunters, photographers, climbers, and tourists who visit the alpine is not known, but it is a safe estimate that they exceed the number of skiers many times. It is not within the scope of this analysis to undertake studies of alpine recreational problems; however, a true evaluation of the zone would be incomplete without mentioning these aspects.

PAST WORK

Only a few references to hydrologic studies of the high alpine area can be found in the literature. Lawrence (1953), in his report concerning water-power resources of the Crystal River in south-central Colorado, shows that runoff from the narrow, steep valleys increases sharply with elevation. Schuman and Costello (1951) give both runoff and precipitation data in their account of range conditions in the Rocky Mountain alpine type. These data are very general, since the study was primarily an ecological investigation of land-use patterns rather than of hydrologic problems.

Climatological data from the alpine area have been taken at only a few places. Dodds (1917) summarized several years records taken at Corona, Colorado. Similar summaries were presented by Whitfield (1933), for data taken on Pikes Peak. More recent records are available from the unpublished reports and records of the avalanche forecasting stations at Berthoud Pass and Arapaho Basin ski area. These records include special data concerning snow pack conditions as well as the regular climatological data. In addition, there are two studies now under way that should contribute additional information. One, being carried out west of Boulder, Colorado, includes a series of weather stations extending from 7,000-12,200 feet, which have been maintained for 4 years. The other, carried out during the summer months only, in the Rawah wild area west of Fort Collins, Colorado, includes wind and precipitation measurements from different elevations on the same mountain, as well as complete climatological data from a base camp near 10,000 feet elevation. It is unfortunate that no attempt has been made to assemble and analyse these fragmentary records so that a complete picture of the climate of the high alpine could be compared to the climate of alpine areas in other parts of this and other countries.

Detailed studies of the alpine snow pack have been carried out as part of the avalanche forecasting program. For the past 4 or 5 years, records have been taken of various physical characteristics of the snow pack which are considered important in the build-up of avalanche hazard. Experienced observers have developed sufficient

skill to permit them to subjectively integrate these factors into reliable avalanche hazard forecasts for the immediate area (U. S. Forest Service Avalanche Handbook, undated).

Much of the best snow research carried out in Europe is summarized in "Snow and its Metamorphism" (Bader and others, 1954). This complete report covers the mineralogical, structural, and mechanical characteristics of snow, as well as field and laboratory procedures for studying snow. Many of these findings are applicable to the high alpine snow pack; however, the cold, windy, continental weather associated with the high alpine zone may present special problems not found at the European study sites.

The snow investigations carried out by the Corps of Engineers and the U. S. Weather Bureau at snow laboratories in the mountainous sections of California, Oregon, and Montana, have resulted in the publication of a complete set of hydro-meteorological data for the several laboratories, as well as numerous research notes. The latter are concerned primarily with the correlation of radiation and weather data with snow melt, and evaporation and condensation from a snow surface. These data are summarized in a detailed report published in 1956 (Corps of Engineers, 1956). Again it is felt that these data, mostly from maritime climates and mostly from below 8,000 feet, will only be indicative of events under the high alpine conditions in the Rocky Mountain region.

Preliminary studies of high alpine snowfields under summer conditions were carried out during the summers of 1955 and 1956 in the Front Range of Colorado (Martinelli, 1956). These studies revealed

snow densities above .7 for most of the summer, and an average vertical ablation of 2 feet per week for the 2-1/2 months following July 1, 1955 (Fig. 4). During July and August, 1955, ablation released about 13 acre-feet of water for each acre of snow existing on August 1. About 95 percent of this melt-water was available for streamflow under the existing conditions, according to calculations using Sverdrup's (Light, 1941) equation.

Evidence of the effect of alpine snowfields on sustaining late summer streamflow was obtained from a direct comparison of snowfield areas and streamflow records for Glacier Creek and Middle Boulder Creek. These are the only streams draining the eastern side of the Front Range between Mt. Evans and Milner Pass that have no unmeasured diversions above the gaging sites.

The two small watersheds are very similar in most respects. Glacier Creek has an area of 25.2 square miles of drainage area above 8,300 feet, while Middle Boulder Creek drains an area of 35.5 square miles above the same elevation. Both extend to the Continental Divide where ridge elevations vary from 12,000 to 12,500 feet. Peaks extend to 12,900 feet on Middle Boulder Creek and to 14,255 feet on Glacier Creek. Both watersheds contain numerous lakes along the tributaries and major streams. Soil and vegetative patterns are also similar for the two areas. The most distant point in the Middle Boulder Creek drainage is about 9-1/2 miles from the gaging station, while the corresponding point in Glacier Creek drainage is only 6-3/4 miles from the gaging station. The major difference between the two watersheds is the amount of snow. At the end of September

Figure 4.--Exploratory studies indicated that alpine snowfields were from 25 to 35 feet deep at the beginning of June. During the summer months snow densities and ablation rates were high while evaporation losses from the snow surface were low. These factors indicate that such snowfields are an important source of summer streamflow.

1953, Glacier Creek had an average of 2.5 acres of snow per square mile of drainage area above 8,300 feet, while Middle Boulder Creek had 0.83 acres of snow per square mile of drainage area above that elevation (Table I).

Judging from the physical characteristics of the basins, disregarding the snow cover, one would expect only minor difference in the streamflow patterns of the two streams. Furthermore, the larger watershed and the lower average gradient in Middle Boulder Creek would indicate that whatever difference did occur would be in favor of a more prolonged flow in this stream. An examination of the streamflow records for the two streams, however, shows the contrary to be true.

The most logical reason for this departure from expected discharge patterns is the large amount of snow in the Glacier Creek watershed. During July when the two streams carried equal proportions of their annual flow, both drainages undoubtedly contained large amounts of snow. Later in the summer, when the general snow cover had melted and only the semipermanent snowfields were left, the discharge rates of the streams reflect the amounts of snow remaining in the two areas.

In Utah Lull and Orr (1950) investigated the possibility of using wind barriers on windward slopes to increase the amount of snow available for streamflow. Results indicate that water released from the induced drifts reached the stream 1 to 1-1/2 weeks after the peak flow. Thus, the drifts seemed to serve two important

Table 1.--Physical characteristics and mean monthly streamflow for Middle Boulder and Glacier Creeks

Summer 1953

	Physical Characteristics	
	Middle Boulder Creek	Glacier Creek
Area	35.5 sq. mi.	25.2 sq. mi.
Most distant pt.	9.5 mi.	6.75 mi.
Amt. of snow (Sept. 27, 1953)	0.83 ac/sq.mi.	2.5 ac/sq. mi.
	Streamflow (cu. ft./sq. mi.)	
July	202 (20%)1/	157 (20%)1/
August	80 (8%)	115 (15%)
September	22 (2%)	42 (5%)

1/ Percent of annual streamflow - U.S.G.S. records

functions. First, they reduced the peak flow; second, the delayed melt helped to maintain high streamflow further into the summer when the need for water is more acute.

PROBLEMS

The need for water in the high plains country east of the Rocky Mountains is a problem of great concern. There is an ever-increasing demand for more water to satisfy municipal, agricultural, and industrial needs throughout the entire region. To complicate the problem, peak streamflow usually takes place a full month before water demands reach their peak, a result of heavy mid-summer agricultural and municipal needs.

Although numerous watershed studies and investigations have been carried out in the Rocky Mountain area during the past 40 - 50 years, almost without exception, these have been concerned with problems and conditions in the forest and grazing land below timber line. As a result of this concentration of watershed research at the lower elevations, very little is known about the contribution of alpine areas to streamflow. There is good reason to believe, however, that the alpine areas with their lower temperatures, numerous late-lying snowfields, extensive bogs, areas of frozen subsoil, and sparse vegetation are an important source of late summer and autumn streamflow. It is also felt that some or all of these factors act as a counterbalance against the occasional very dry year.

The major problems of the alpine area from the standpoint of snow and hydrologic research are enumerated below:

1. How to increase the water yields coming from alpine watersheds, especially during the summer months.

2. The evaluation of late-lying alpine snowfields in the overall hydrologic picture of the alpine.

3. The interpretation and the integration of snow and climatic data taken in other parts of the United States and in Europe in terms of prevailing climate, topography, and snow conditions of the high alpine areas of the Rocky Mountains.

4. How to integrate meteorological, topographic, and snowpack information into a simple, reliable mechanism to predict the extent and intensity of avalanche hazard.

5. How to reduce avalanche hazards at special heavy-use areas by stabilizing snow on dangerous slide paths, preventing the accumulation of snow on avalanche areas, maintaining an adequate vegetative cover, and by the use of special structures.

MAJOR OBJECTIVES

The major objectives of Alpine Snow and Hydrologic Research are listed below, but not necessarily in the order of their importance. The long-term nature of some of the primary objectives will make it possible to carry out short-term studies of lower priority while the long-term studies are still in progress.

1. To develop and test methods and techniques for inducing additional snow accumulation in natural catchment areas within the alpine zone to increase summer streamflow.

2. To locate and measure the alpine snowfields in a representative portion of the Front Range at the beginning and end of the same summer, in order to compare them with measured streamflow.

3. To collect, compile, and analyze climatological data from selected alpine locations and to study the distribution of precipitation with altitude in order to compare these areas with other places where extensive snow research has been carried out.

4. To study the basic physical and meteorological phenomena associated with the occurrence, accumulation, metamorphism, and disappearance of snow in the alpine zone.

5. To determine the runoff from selected alpine watersheds.

6. To develop a more objective means of predicting the extent and intensity of avalanche hazard based on weather, climatological, snow structure, and orographic data.

7. To aid the Division of Range Management Research, Rocky Mountain Experiment Station, on certain phases of their alpine grazing project.

8. To set up studies to determine the importance of

(a) infiltration capacity of alpine soils

(b) alpine bogs

(c) permafrost areas

(d) lake patterns on the regimen of alpine streams

SPECIFIC STUDIES TO ACHIEVE MAJOR OBJECTIVES

Studies will be listed under only one research objective in spite of the fact that many of them will bear on more than one objective. The descriptive material under each study will indicate which of the other objectives it will help achieve.

Major objectives will be restated and the specific study, or studies, designed to achieve it will be listed and described briefly.

1. To develop and test methods and techniques for inducing additional snow accumulation in natural catchment areas within the alpine zone to increase summer streamflow.

(a) Accumulation of Snow in Alpine Areas and Means of Influencing It . . . This study will have several phases. During the first year several patterns of snow fencing will be tested at Berthoud Pass where frequent observations can be made. Another test of fence location in relation to a natural catchment basin will be made at Mt. Evans where 2 years of records have been taken.

During the winter of 1957-58, the rate of snow accumulation in a number of small natural catchment basins at the

Loveland Ski Area will be determined. Periods of maximum accumulation will be correlated with synoptic weather conditions. A complete weather station will also be installed and maintained adjacent to the study sites. Snow depths, densities, and associated features will be measured on these drifts until all snow disappears. Data taken at the Loveland Ski area will be in the nature of a pre-treatment calibration for 8-12 small natural catchment areas. After sufficient calibration, certain of the catchment areas will be chosen to test the effectiveness of the most satisfactory snowfence patterns and locations resulting from the Berthoud Pass and Mt. Evans tests. The other catchment areas will serve as controls (Figs. 5 and 6).

(b) Paired Watershed Study . . . Should the Loveland Basin tests indicate that fencing will significantly increase the amount of snow held in natural catchment areas, a paired watershed study will be started to determine if such fencing can make significant change in the amount and distribution of water released for streamflow. In order to carry out this phase of the study, two watersheds will be gaged long enough to develop a regression for predicting the streamflow of one as a function of the other. Snow barriers will then be constructed in one of the watersheds in an attempt to create the maximum number of deep drifts.

Figure 5.--The depth of snow accumulating in alpine snowfields is a function of the height of the wind barrier behind which the drift forms. In this case the small ridge in the right middle ground was only tall enough to create an 8-foot drift. It is felt that such snowfields could be greatly deepened and enlarged if the natural barrier could be supplemented by an artificial one.

Figure 6.--These snowfences are part of an experiment to test the relative effectiveness of 4 different fence patterns. Once an effective pattern has been chosen, fences will be built at drift sites to see if natural drifting can be supplemented.

A comparison of the actual streamflow from the treated watershed with the flow predicted by the regression will indicate the effectiveness of the treatment in producing more late summer flow.

2. To locate and measure the alpine snowfields in a representative portion of the Front Range at the beginning and end of the same summer.

   (a) One set of aerial photographs will be taken of a selected portion of the Front Range of Colorado in June. A second set will be taken of the same area in September of the same year. The amount of snow that disappeared during the summer will be determined by subtracting the amount of snow found on the September photographs from the amount found on the June photographs. These snow area data can then be combined with density, melt, and evaporation data from contemporary studies to estimate the water yield from the alpine snowfields. The aerial photographs will also be used in the development of a classification of alpine areas based on the propensity for snow to drift, as well as in the selection of sites for future alpine studies.

3. To collect, compile, and analyze climatological data from selected alpine locations and to study the distribution of precipitation with altitude in order to compare these areas with other places where extensive snow research has been carried out.

(a) High Alpine Weather Studies . . . These studies will be two-phased. The first phase will involve the collection of climatic records now being taken at ski areas, cosmic ray installations, avalanche study sites, and other places in the high alpine zone of the Rocky Mountain area. The second phase will include the establishment of weather stations at several places within or immediately adjacent to alpine areas where volunteer observers can be recruited. Instruments and technical assistance will be provided the observers by the Experiment Station or its cooperators. It is thought that such arrangements can be made at several of the lodges that employ year-long caretakers, many of the ski areas, and the Rocky Mountain National Park. Every effort will be made to have these data published by the Weather Bureau. In addition, all data will be compiled and analyzed by Experiment Station personnel in order to compare it with similar data taken in other alpine areas of this and foreign countries. Such a comparison should be a great aid in the interpretation of snow and avalanche research carried out in Europe, the Sierras, and elsewhere in terms of prevailing conditions in the high alpine areas of the Rocky Mountains.

(b) High Altitude Precipitation Patterns . . . A series of precipitation gages will be installed from some established alpine weather station, such as the one at Berthoud

Pass, to one of the nearby summits. Data will be taken after each storm and will be analyzed so that elevational and synoptic variations in precipitation can be compared. The location of such a series of gages will be dependent upon the location of suitable slopes near established weather stations. A better understanding of how precipitation varies with altitude should aid in locating snowfences in places where they will be most effective.

4. To study the basic physical and meteorological phenomena associated with the occurrence, accumulation, metamorphism, and disappearance of snow in the alpine zone.

(a) Snow Density Study . . . Alpine snow under winter and spring conditions has been found to have a maximum density of about .30 to .35. On the other hand, studies of alpine snow under summer conditions show densities as high as .60 to .70 in mid-June. A continuation of the spring studies until mid-summer should indicate what factors cause this sharp increase in density and when it takes place.

(b) Factors Influencing the Formation of "Depth Hoar" . . . Layers of coarse-grained snow showing large distinct crystal structure and very little cohesion are called depth hoar (Bader and others, 1954). Such layers usually form near the ground; hence, on steep slopes they are often associated with avalanche activity. In

spite of intensive snow research in Europe, the manner in which depth hoar forms has not been explained satisfactorily. Depth hoar under the snowpack on steep slopes is considered the primary cause of avalanches in the Rocky Mountains; hence, the most effective avalanche prevention methods will involve an understanding of how such depth hoar forms so that steps can be taken to eliminate it on dangerous slopes.

(c) Non-Catastrophic Movements Within the Snow Pack . . . Present techniques to separate the vertical component (settlement) from the downslope component (creep) of movement within the snow pack are time-consuming and arduous. Techniques and/or instrumentation are needed to measure these components of intra-pack movement quicker and with less disturbance to the pack. Such measurements, particularly if they can be recorded continuously, may help determine if creep or settlement rates increase or decrease sharply immediately prior to the release of avalanches. A major part of this study will probably involve the design and construction of special instruments to measure creep and settlement independently.

(d) Surface Anomalies . . . Snow surfaces will be dated with oil soluble dyes as the snow pack accumulates during the winter. Special effort will be made to mark and photograph

winter surfaces that have a distinctive pattern of wind ripples, scallops or cups. The reappearance of these surfaces during spring melt will be noted and described (Fig. 7). In this way, it should be possible to determine whether patterned snow surfaces which appear during the spring and summer months are produced by winds and evaporation that took place in the winter, or are formed by summer conditions. Such surfaces have occasionally been cited as evidence that snow at high elevations evaporates or sublimates and, therefore, produces little or no melt water for streamflow. Preliminary tests and observations in the Rocky Mountains do not confirm this.

(e) Gage Melt Water Released from an Alpine Snowfield . . . The primary objective of this study would be to get a direct measure of the water released by the ablation of an alpine snowfield. All previous work has involved estimating melt water volumes from ablation and density data. A secondary objective would be to correlate streamflow with weather factors and the decrease in water potential of the snowfield as determined from ablation and density data. The study will be carried out at one or more alpine snowfields having most of the following characteristics:

(1) Located near the top of a ridge or divide to reduce the confounding factor of drainage into the gaged basin.

Figure 7.--Two types of snow surface anomalies are illustrated. (A) The conical mounds had no apparent pattern or orientation. Each mound had a small dirt cap which partially insulated it from the sun. (B) The wave pattern was noticed at the end of August. The ripples were oriented roughly parallel to the contours. It is not clear whether these patterns formed under winter or summer conditions, nor is it certain whether they result from wind or evaporation.

(2) Distinct melt water stream with good gaging site near the edge of the June 30 snowline.

(3) Snowfield of moderate size (less than 10 acres on June 30) that melts out most years.

(4) Accessible to truck travel during summer months.

A stream gage of suitable type will be installed and equipped for continuous operation during the melt period (Fig. 5). A weather station providing continuous records of temperature, wind velocity and direction, precipitation, humidity, and all-wave radiation will be maintained during the melt period. In addition, periodic measurements will be taken of the surface area, density, and ablation rate of the snowfield.

(5) Snow Lysimeter Studies . . . The primary objective of these investigations will be to study evaporation and condensation from a snow surface under summer conditions in the high alpine. Plastic or metal containers will be filled with a known amount of snow and exposed to atmospheric conditions. Provisions will be made to permit melt water drainage to be measured. Frequent weighings will give an indication of the addition (condensation) or loss (evaporation) of water from the sample. These findings will then be compared to evaporation and condensation estimates made by use of the several physical equations available in the literature. Several "runs"

Figure 8.--During the summer of 1955 meltwater from an alpine snowfield was measured each week in the manner illustrated. The data indicated the need for continuous streamflow records if runoff is to be correlated with snowmelt and weather information.

will be made during the summer in an attempt to sample weather conditions.

(6) Means of Regulating Alpine Snowmelt . . . Designated areas on an alpine snowfield will be treated with different concentrations of non-water soluble black substances, such as aqua nuchar lamp black, etc., to determine if snowmelt can be increased significantly (Fig. 9) A statistical design will be selected to permit the evaluation of different amounts and different methods of application. Snow stakes will be used to measure the rates of vertical ablation in both treated and control areas (Fig. 10). Such studies will permit the necessary replications of treatments. However, it will not permit the direct measurement of melt water released. Should such studies offer promise and more elaborate tests appear justified, they could be carried out either on large lysimeters or in small paired watersheds where melt water could be measured directly.

5. To determine the runoff from selected alpine watersheds.

(a) A check of available literature will be made to get records of water yields and duration of flow by altitudinal zone. It is thought that few records of this type exist for the western mountains.

Figure 9.--Materials such as sawdust, soil, and lamp black, when placed on the snow surface, influence the rate of melt. Sawdust and soil slow the melt. Carbonblack, when applied in a thin layer, speeds the melt.

Figure 10.--A fast, simple way to measure melt rates is illustrated above. Stakes of known length were sunk to the ground in the center of each test plot. Current snow depth was read from the calibrated staff.

(b) Depending on the accessibility of the areas, 2 to 4 streams or chains of lakes will be gaged. Every effort will be made to select watersheds that extend well into the alpine, are accessible, and contain several good natural gaging sites in the upper reaches; other things being equal, top priority will be given to streams that are currently being gaged at lower elevations. Water yield data will be taken at several places on the upper reaches of each stream. Gaging sites will be chosen with an elevational difference of about 1,200-1,500 feet if possible. It is thought that at many sites it will be possible to install water level recorders in lakes and to rate a natural stream section nearby using a velocity head rod or a current meter in order to develop a rating curve (Fig. 11). At other places it may be necessary to install stilling wells and/or to improve the stream section. However, in the preliminary phases of this study, installations will be minimized.

The stream gages proposed for this study will be for experimental purposes and are not suggested as long-term installation. They should not be considered a duplication of the gaging activities of the U.S.G.S.

Figure 11.--One of the sites where alpine streamflow was measured during the summer of 1956. This site, at an elevation of 10,700 feet, is adequate for current meter readings during the summer months. However, it would not be suitable for a permanent gaging site.

(c) A network of rain gages will be set up in each watershed to permit an estimate of precipitation for each of the altitudinal zones. Although other weather data would be of interest, at this time there appears to be no real need for additional weather data as far as this particular study is concerned.

(d) Water-yield data will be worked up on the basis of yield per unit of area for each altitudinal zone and for each watershed. Because of the great diversity in configuration, orientation, and size of the mountain watersheds, results of this study are not expected to be highly definitive. However, they are expected to be indicative of the relative importance of the altitudinal zones as water producers.

6. To develop a more objective means of predicting the extent and intensity of avalanche hazard based on weather, climatological, snow structure, and orographic data.

(a) Records of avalanche activity will be correlated with weather, climatic, snow structure, and orographic data in order to test the relative importance of the various factors (Fig. 12). Intensive field testing and observations will be concentrated on factors found to be important contributors to avalanche hazard, plus

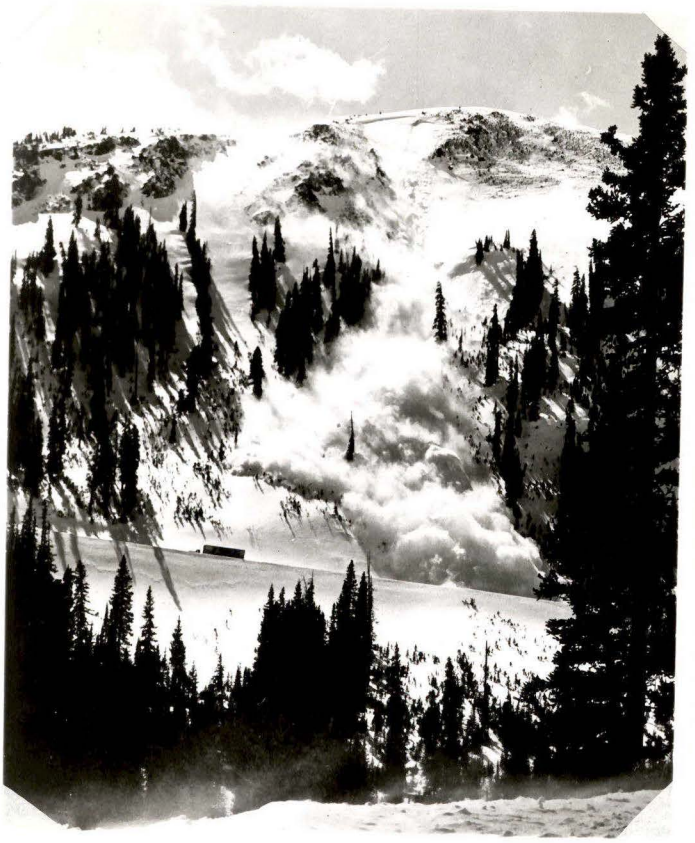

Figure 12.--There is an ever-increasing need for an objective means of predicting the liklihood of avalanches. There is also a need for better information on how structures or terrain modifications could be used to reduce the hazard from such slides when they do occur.

such factors as humidity and radiation, which are not commonly measured, but are thought to be important. The ultimate goal of such a study would be an avalanche hazard scale comparable to the fire danger ratings in common use. A first approach will be to set up a multiple correlation analysis using the data taken at Berthoud Pass during the past 4 or 5 years.

7. To aid the Division of Range Management Research, Rocky Mountain Forest and Range Experiment Station on certain phases of their alpine grazing project.

   (a) Alpine grazing studies are still in the formative stage. Tentative plans are to evaluate range management practices from both the grazing and watershed standpoints. Depending on the final study plans such weather factors as precipitation, temperature, wind and humidity, and such hydrologic factors as streamflow and sedimentation may be of interest to the range investigations, but will be measured in cooperation with the alpine snow and hydrologic studies.

8. Set up studies to determine the importance of (a) infiltration capacity of alpine soils, (b) alpine bogs, (c) permafrost areas, and (d) lake patterns on the regimen of alpine streams.

   (a) Formal studies on this phase of alpine hydrology will be drawn up after the completion of the studies listed under Objectives 1 through 7.

As an aid to carrying out the research program outlined above, a series of winter meetings will be started for research workers interested in alpine problems. Current and proposed alpine studies will be discussed with all research workers in the Rocky Mountain area who are either working on, or interested in, alpine problems of any type. It will be suggested that such meetings be held at the various universities within the State, at fixed dates to be decided upon by the group.

POSSIBILITIES FOR COOPERATION

There are many possibilities for cooperation on the proposed alpine studies. Numerous government agencies, universities, and individuals are currently engaged or greatly interested in alpine problems. Many of the possible cooperators listed below have been contacted and are either cooperating now, or are willing to take an active part in future alpine studies.

1. Government Agencies:
   (a) National Forest Administration - avalanche studies and use of study sites.
   (b) Corps of Engineers, U. S. Army - weather instruments and equipment.
   (c) Bureau of Reclamation
   (d) Snow, Ice, and Permafrost Research Establishment (SIPRE)- technical advice and possibly instruments and equipment
   (e) Weather Bureau

(f) National Park Service - Use of study sites and possibly aid in servicing meteorological instruments.

2. Universities, or University Research Organizations:

(a) Institute of Arctic and Alpine Research, University of Colorado, Dr. Marr - housing and possibly climatic records.

(b) Solar Observatory, University of Colorado, Dr. Roberts - possibly climatic records from Climax, Colorado.

(c) Inter-University High Altitude Laboratory, Denver University, Dr. M. Ives - Housing and weather records from Mt. Evans.

(d) Department of Zoology, Colorado State University - Dr. John Olive - Streamflow and climatic records from the Rawah Mountains.

3. State and Municipal Agencies:

(a) Highway Department - possibly avalanche and climatic data

(b) City of Boulder - use of a study area and possibly streamflow data

4. Private Organizations:

(a) United Air Lines, Mr. Harrison - meteorological data and possibly observations of turbulent conditions over the mountains.

(b) National Ski Patrol - Possibly help rescuing instruments and taking snow observations

(c) Ski Area Operator, Loveland Basin Ski Area - Housing and help with drift study.

5. Individuals:

(a) Whitney M. Borland - avalanche and weather data.

(b) Certain caretakers at all-year lodges, such as those at St. Mary's Glacier and Duck Lake. Possible volunteer weather observers.

(c) Other research workers in the Rocky Mountain area - through the medium of winter seminars on alpine problems.

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